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TECHNIQUE FOR THE SIMULATION OF LUNAR AND PLANETARY GRAVITATIONAL FIELDS INCLUDING PILOT MODEL STUDIES

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SUMMARY

A technique for simulation of landing dynamics in lunar and planetary gravitational fields is presented. The basic principles of the technique involve dropping the spacecraft (or payload) onto an appropriate impact surface which is undergoing the desired acceleration relative to the freely falling spacecraft or payload. An effective gravitational acceleration equal to the difference between the acceleration of gravity on the Earth and the acceleration of the impact surface is then experienced by the vehicle at impact. The performance of a pilot model simulator which utilizes the technique was also evaluated. Studies were conducted in the simulator to determine the effect of reduced gravitational acceleration on the behavior of simple models during landing. Markedly reduced tipover stability was demonstrated for the impact of the models onto a sandy surface and for the case in which the model collided with an obstacle shortly after landing. A brief discussion of the effects of a reduced gravitational acceleration on the behavior and the trajectory of surface particles dislodged by the landing gear footpads is also presented.

INTRODUCTION

The simulation of landing loads in lunar and planetary gravitational fields is complicated by the fact that the gravitational acceleration at the surface of the Moon and planets varies considerably from that at the Earth's surface. The primary difficulty is the simulation of the loads and attitude stability of a vehicle subsequent to the initial impact. During the initial impact, these loads are primarily dependent upon the structure of the vehicle, its impact momentum and attitude, and the nature of the target. The motions of the vehicle following the initial impact and its attitude upon subsequent impacts (i.e., its stability) are highly dependent on the magnitude of the gravitational attraction. Thus, proper simulation of the acceleration due to gravity is essential for assurance of attitude stability and structural integrity during the landing process.

In order to conduct landing dynamic studies on extraterrestrial spacecraft one of two methods is usually employed: (a) the use of dynamic models, properly scaled to represent gravity differences or (b) full-scale vehicles tested under simulated gravitational acceleration. The use of scaled models for experimental purposes is a well established practice. Since the gravitational acceleration at the lunar surface is 1/6 that present at the Earth's surface, dynamic similarity during free-fall drop tests on the Earth's surface is achieved if the replica model is 1/6 the size of the lunar vehicle. However, this imposition requires that all the nonlinearities of the landing gear must be duplicated in a small model - often an extermely difficult task. But, of greater significance is the fact that realistic preflight tests of the actual vehicle cannot be conducted by landing the vehicle on the surface of the Earth.

The second alternative is to simulate the necessary gravitational acceleration. Reference 1 discusses briefly various techniques by which this simulation may be achieved. Most of these methods utilize a cable attached at the center of gravity of the vehicle to support a part of the vehicle mass.

The purposes of the present paper are twofold: First, to describe a technique which utilizes the principle of the Atwood machine (ref. 2) for simulation of lunar and planetary gravitational accelerations; and second, to present some results of experimental studies conducted with a pilot model of such a simulator. The technique offers the advantage that the vehicle is not restrained by encumbering cables which eliminates the varying gravitational acceleration imposed on the model during impact. The pilot model studies were designed to establish and demonstrate the feasibility of the simulator concept and to provide data on the behavior of several small models impacting under reduced gravitational acceleration.

A motion-picture film supplement showing the operation of the pilot model of the lunar and planetary gravitational simulator is available on loan. A request card form and a description of the film will be found on the page with the abstract cards.

SYMBOLS

a acceleration, ft/sec^2

g gravitational acceleration at Earth's surface, ft/sec^2

I mass moment of inertia of flywheel, lb-ft-sec^2

M mass, lb-sec^2/ft

n ratio of gravity simulated to Earth gravity; $n = 1/6$ for Moon

r radius of winch, ft

t time, sec

v impact velocity, ft/sec

Subscripts:

1	simulator housing
2	retarding mass or counterweight
x	horizontal component
y	vertical component

APPARATUS AND TEST PROCEDURE

Simulator Concept

The basic principle of the lunar and planetary gravitational simulator is discussed in reference 3 and involves dropping the payload onto a relatively massive impact surface which is undergoing the desired acceleration relative to the freely falling spacecraft or payload. The effective gravitational acceleration acting on the spacecraft during impact is then the difference between Earth "g" and the acceleration of the impact surface.

The general configuration of the gravity simulator is depicted in figure 1 and consists of an impact surface and housing M_1 connected by a cable or cables passing through overhead pulleys to either a counterweight M_2 or an inertia wheel.

During a typical test sequence the vehicle or payload is released at the desired horizontal velocity from a suitable mechanism located above the impact surface. The payload then gains the desired vertical impact velocity by free fall under 1 g conditions. Just prior to impact of the test vehicle on the surface, the masses M_1 and M_2 are permitted to accelerate by releasing brakes on the cables.

At the end of the test period, the complete system is brought to rest by means of an arresting device.

If counterweights are utilized, the downward acceleration of the simulator is given (neglecting friction and aerodynamic drag) by

$$a = (1 - n)g = g\,\frac{\left(M_1 - M_2\right)}{\left(M_1 + M_2\right)} \tag{1}$$

where n is the ratio of the gravitational acceleration of interest to Earth gravity, and g is the gravitational acceleration at the surface of the Earth. For a particular value of n, the mass M_2 is given by

$$M_2 = M_1\left(\frac{n}{2 - n}\right) \tag{2}$$

For the gravitational acceleration of the Moon, n should be approximately 1/6, therefore

$$M_2 = \frac{M_1}{11}$$

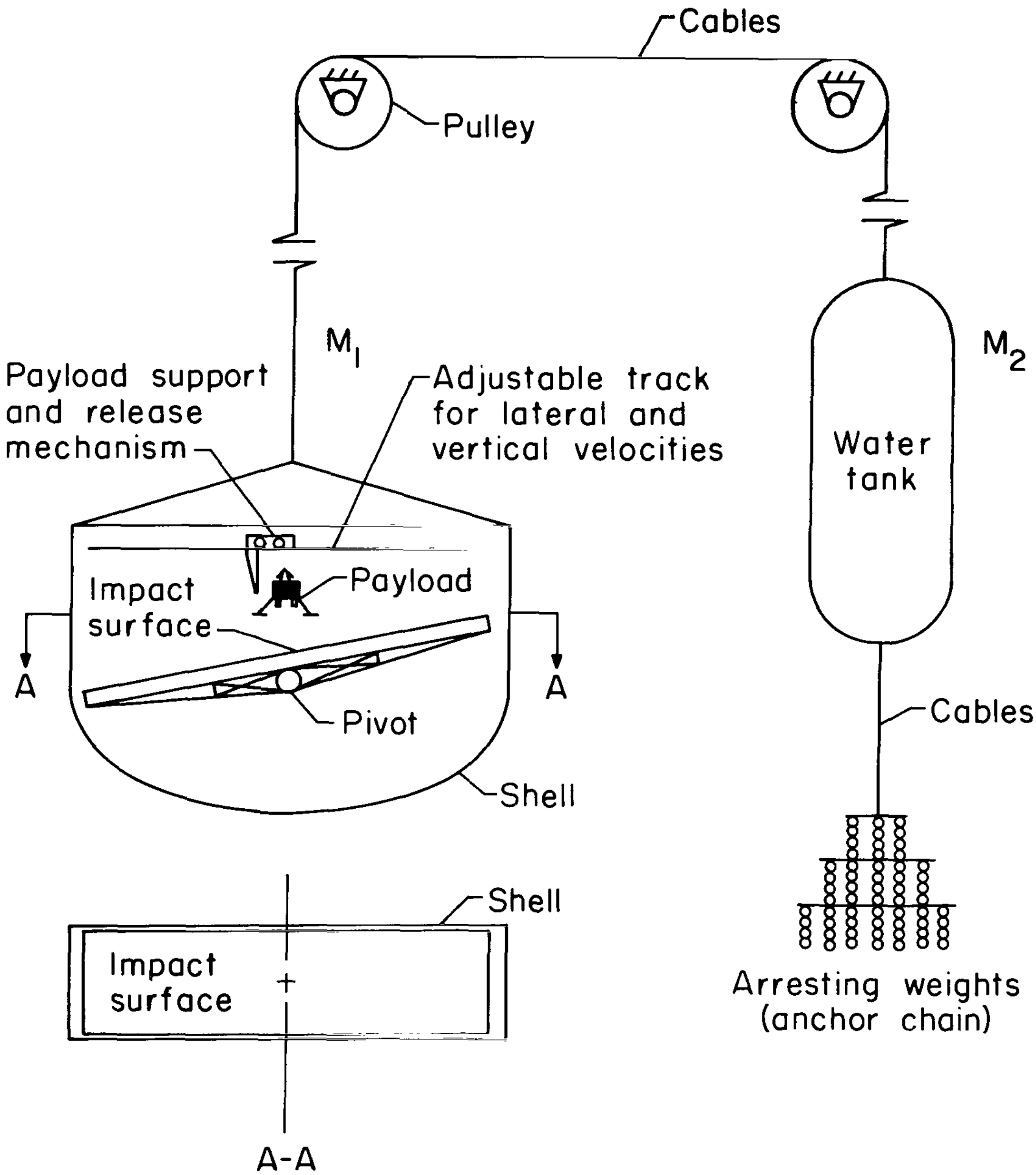

Figure 1.- Lunar and planetary gravitational simulator.

In the simulation of gravitational accelerations greater than that of the Earth, the impact surface would have to be accelerated upward. Equation (2) shows that the maximum theoretical limit on the gravitational acceleration which could be simulated with the technique without the use of mechanical advantage is a 2g field. From a practical standpoint the limit would, of course, be somewhat lower than 2g. It is significant to note that the gravitational acceleration of all the planets, with the exception of Jupiter (2.65g), could be simulated by this technique.

The pilot model of the simulator constructed at the NASA Langley Research Center, and reported herein, utilized an inertia wheel to replace the mass M_2. The proper inertia is given by the relationship

$$I = M_1 r^2 \left(\frac{n}{1 - n}\right) \tag{3}$$

where r is the radius of the winch. Equation (3) shows that this technique can be used to simulate any gravitational acceleration less than that of the Earth.

Description of Pilot Model Simulator

The explanation of the basic configuration of the pilot model of the lunar and planetary gravitational simulator is accomplished with the aid of figures 2 to 4. As indicated in figure 2, the mass M_1 is attached to one end of a cable through a hydraulic shock absorber or damper. The mass M_1 consisted of: (1) the simulator housing, (2) the trapeze mechanism for achieving desired horizontal and vertical velocities at touchdown and for supporting and releasing the payload, and (3) the impact surface. The impact surface consisted of a platform or table designed to be tilted about a pivot to provide a range of angles to simulate the slopes of the landing surface at the point of impact of the vehicle or spacecraft. Dust, sand, gravel, or other materials can be placed on the platform to simulate anticipated surface conditions. The other end of the support cable was attached to an inertia wheel, winch, and pneumatic brake assembly anchored to the floor (fig. 3(a)). The total combined weight of the platform and housing was approximately 700 pounds. A total available drop height of 32 feet including an 8-foot braking distance (2g) permitted a lunar-gravity-simulation time of approximately 1.3 seconds.

Instrumentation

Acceleration of the housing and platform was measured with a strain-gage accelerometer. Signals from the accelerometer were amplified and fed into a two-channel d-c amplifier-recorder for direct display and readout. The behavior of the models impacting under both 1g and $\frac{1}{6}$ g was recorded by a high-speed camera located in the housing.

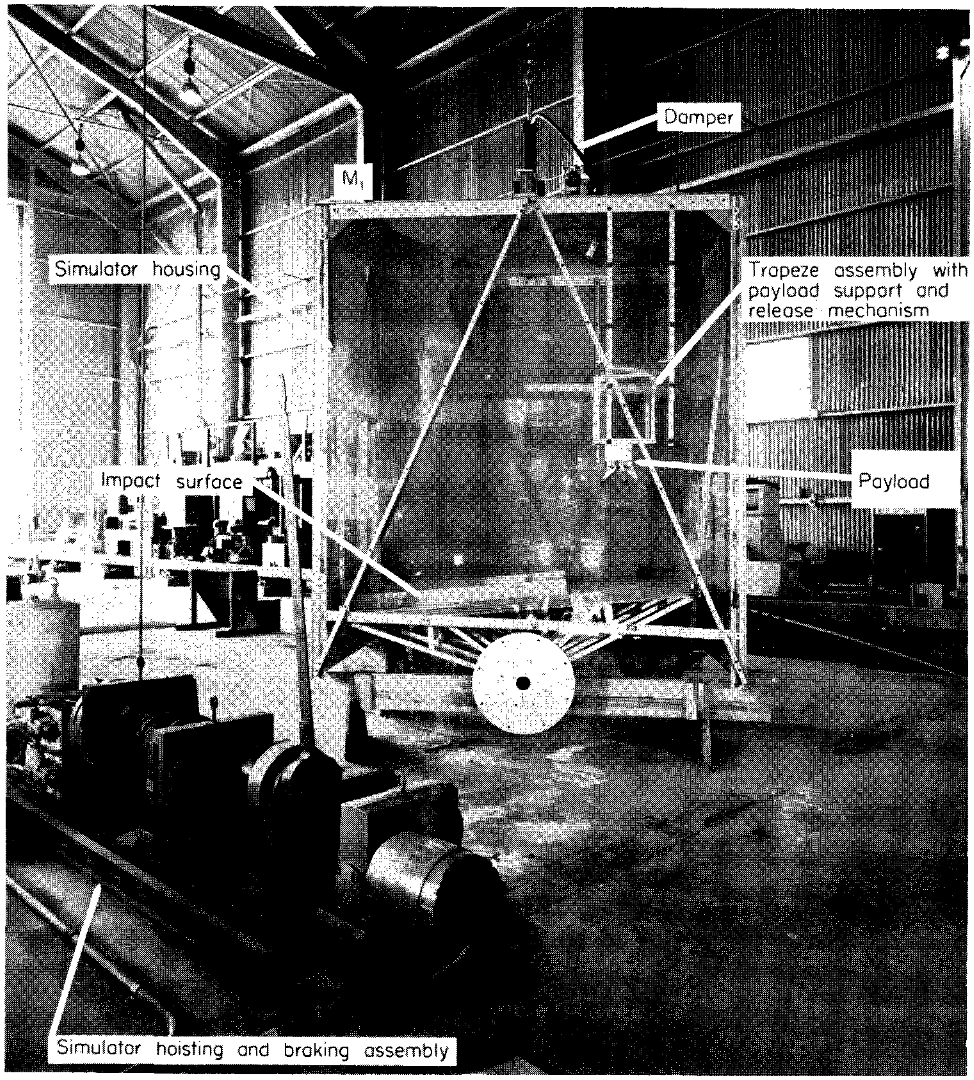

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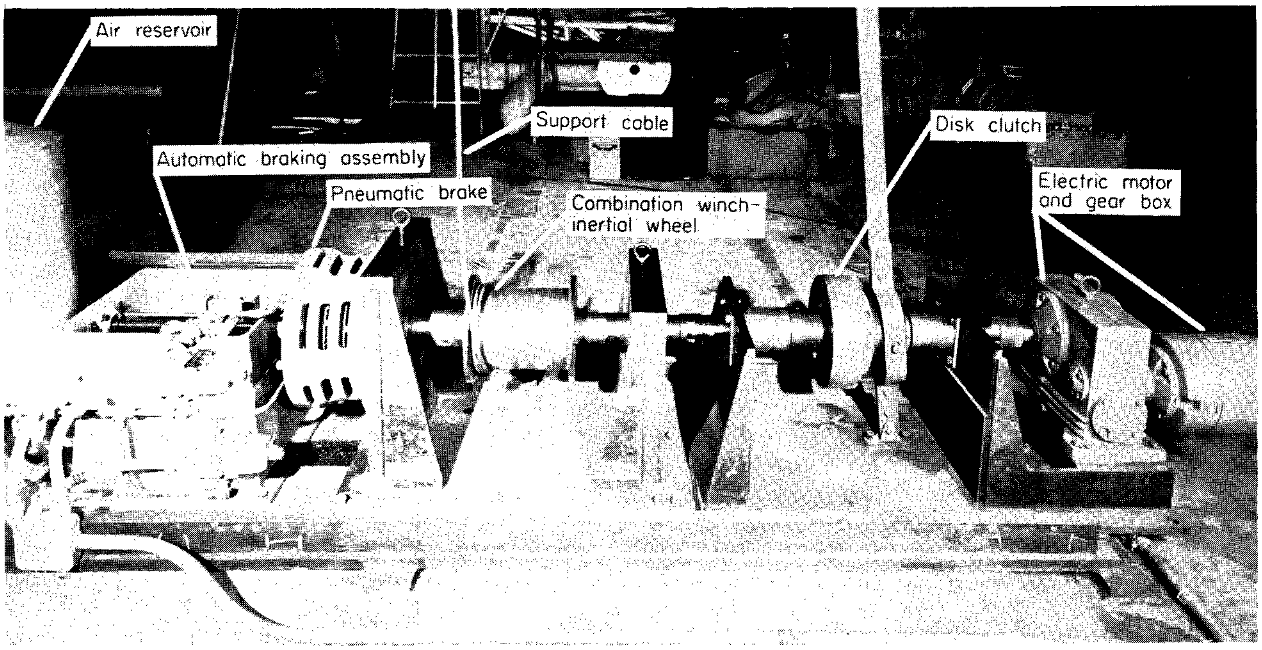
Figure 2.- Pilot model of lunar and planetary gravitational simulator at the Langley Research Center.

Test Procedure

The test sequence was initiated by engaging the disk clutch (fig. 3(a)) and hoisting the assembly to the maximum drop height by means of the electric motor. Limit switches (fig. 3(b)) were actuated by an assembly traveling along a lead screw attached to the shaft of the inertia wheel. Automatic application of the pneumatic brake at the maximum position and shutdown of the electric motor were accomplished by these switches. The disk clutch was then disengaged leaving only the pneumatic brake to hold the assembly.



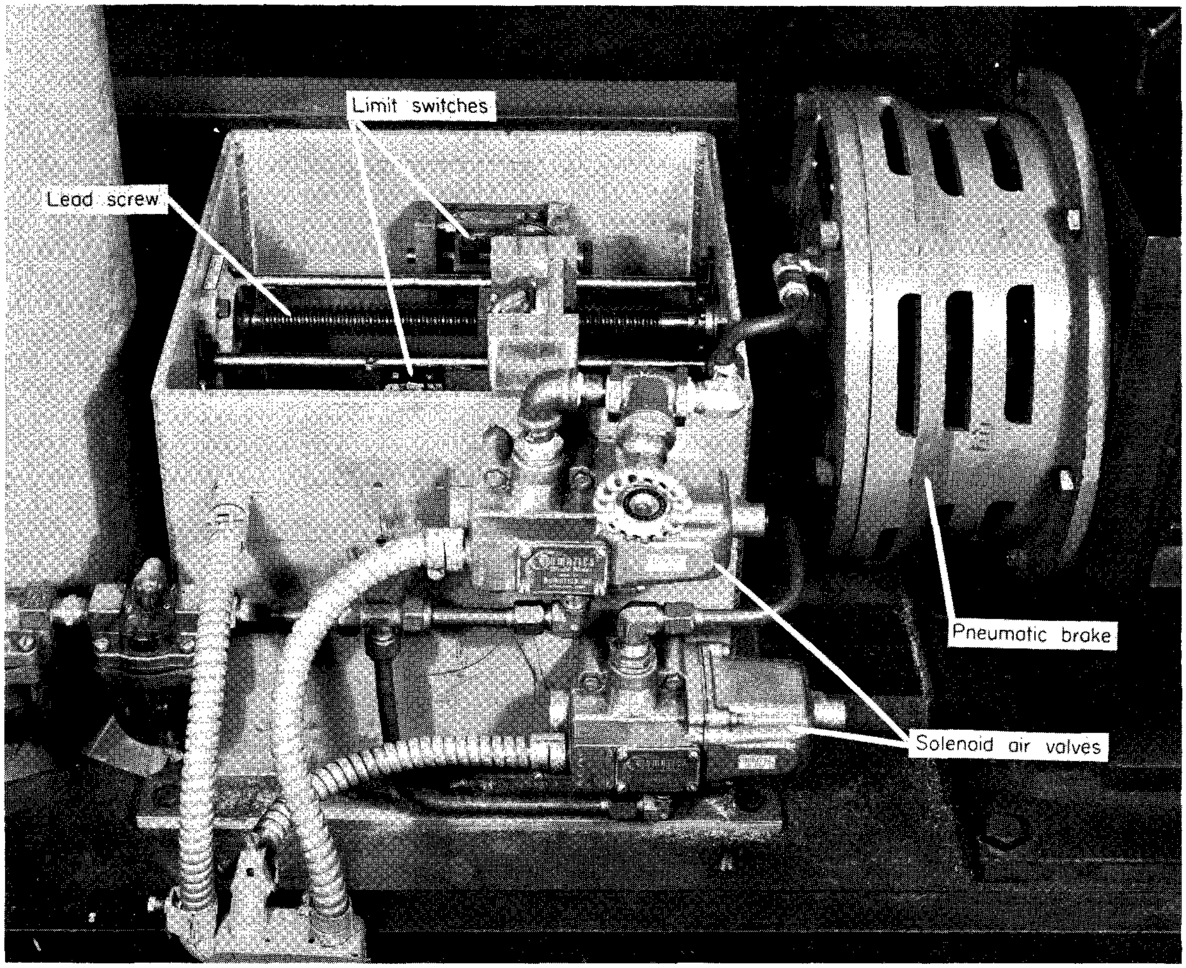
(a) Hoisting assembly. L-64-531.1

Figure 3.- Simulator hoisting and braking assembly.

Figure 4 shows the simulator in an elevated position above the ground with payload mounted to the support and release mechanism. The trapeze arrangement was released, imparting the desired horizontal velocity to the attached payload. At the lowest point of the trapeze swing, the model was released and achieved the desired vertical velocity by free fall under 1 g conditions. Just prior to impact of the model on the surface, the pneumatic brake was electrically actuated to release the inertia wheel assembly. The housing or mass M_1 accelerated downward retarded by the inertia of the wheel. At the end of the test period, limit switches again actuated the pneumatic brake bringing the system to rest at a 2g deceleration rate. The model tests were then repeated under 1 g conditions for comparison.

Description of Test Models

Model A.- The model designated model A is shown in figure 5. The model consisted of a cylindrical body to which were attached five symmetrically located legs. The cylindrical body was 6 inches in diameter and $3\frac{1}{2}$ inches long with 1/8-inch-thick aluminum disks bonded to each end. Body attachment angles, bolted through the lower disk served as mounting fixtures for the legs. Both shock absorbing capability and elasticity were built into each leg assembly. The shock absorbing capability was provided by Coulomb friction between bakelite



(b) Details of automatic braking assembly. L-64-530.1

Figure 3.- Concluded.

disks and the body attachment angles. Spring-loaded bolts allowed the compression between the disk and attachment angle to be varied for changes in the shock-absorbing properties of the legs. Elasticity was provided by constructing the lower half of each leg as a flexure spring.

Model B.- Figure 6 presents the impact model designated model B. This model was a four-leg vertical-strut configuration with a cylindrical body section. The truss geometry and rather massive structural members resulted in an extremely rigid configuration. The center, or body section of the model, was fabricated from a $7\frac{1}{2}$-inch-long 6-inch-diameter steel pipe having a wall thickness of 1/4 inch. No radial or angular shock absorption was available; however, Coulomb friction in the telescoping legs did provide shock-absorption capabilities parallel to the longitudinal axis of the body.

PRESENTATION AND DISCUSSION OF RESULTS

Pilot Model Simulator Performance

Typical results of tests of the gravity simulator pilot model are given in figure 7. A typical acceleration-time history of the simulator housing, taken during initial drop tests, is given in figure 7(a). The figure shows the existence of undesirable oscillations of the simulator which were present throughout the 1.3-second test time. The oscillations after 1.3 seconds are associated with braking and are of no concern except for the loads they impose on the structure and on the model. The oscillations prior to operation of the brake were caused by periodic tensile reactions of the finite length of the elastic support cables. This difficulty was eliminated by the installation of a large hydraulic damper or shock absorber between the cable and the housing. The hydraulic damper is shown in figure 2 and in greater detail in figure 8.

Figure 7(b) is a typical acceleration-time history of the simulator housing obtained with the flow valve on the damper closed. It may be seen that the undesirable oscillations were still occurring during the initial and terminal phases of the drop sequence. These oscillations were eventually eliminated by optimizing, experimentally, the accumulator pressure and flow valve setting. The resultant acceleration-time history of the final configuration is presented in figure 7(c).

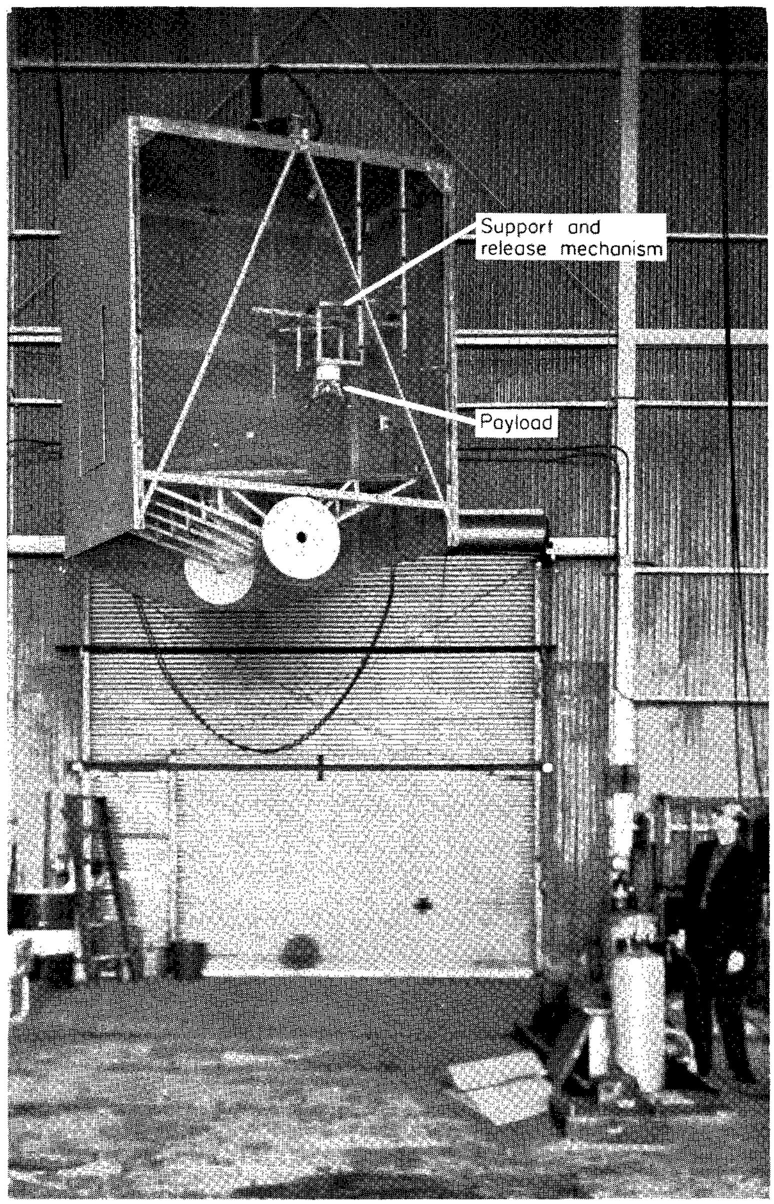


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Figure 4.- Pilot model of lunar and planetary gravitational simulator in an elevated position.

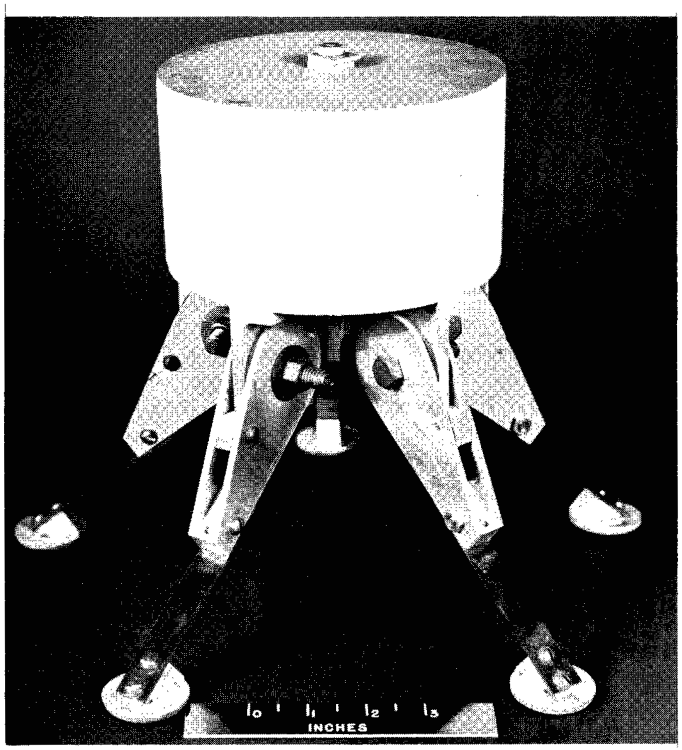


Figure 5.- Model A. L-63-5912

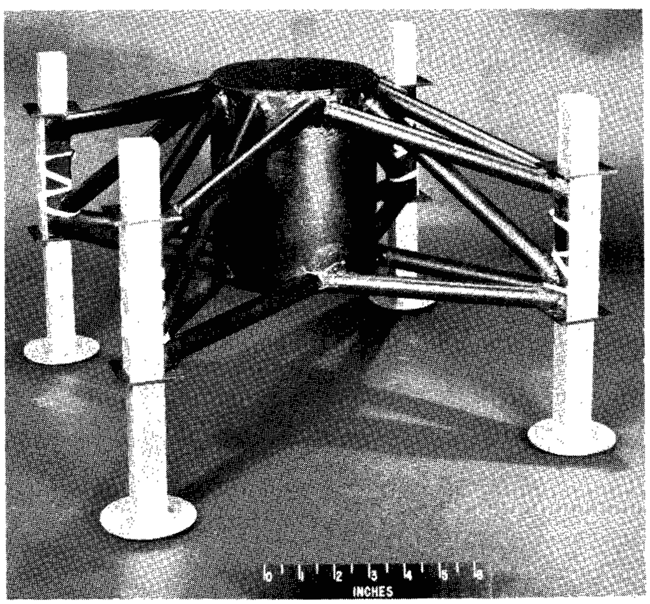


Figure 6.- Model B. L-63-8952

It may be seen that the $\frac{5}{6}$ g period (test time) was free from transient oscillations and the disturbance level during the braking period is much less severe than in figures 7(a) and 7(b).

The total simulator performance was somewhat adversely affected by the addition of the damper in that an extended drop-off time and dynamic overshoot (fig. 7(c)) were introduced before the $\frac{5}{6}$ g condition was reached, thus shortening the usable test time. To make the most efficient use of the available test time, the payload should impact immediately after the impact surface has stabilized at a downward acceleration of $\frac{5}{6}$ g. The necessity for impact to occur under a stabilized downward acceleration would require that the payload be in free fall or, in some instances, swinging on the trapeze during the initial period of unsteady acceleration of the platform; hence, some difficulty may be encountered in accurately controlling very low impact velocities.

Another, possibly more effective, method of eliminating the undesirable oscillations would involve placing the hoist-brake assembly at the top of the simulator-support structure and hoisting the housing up to the inertia wheel thus essentially eliminating the initial cable length and thereby increasing the effective rigidity of the system. The additional advantage of a 50-percent reduction of the

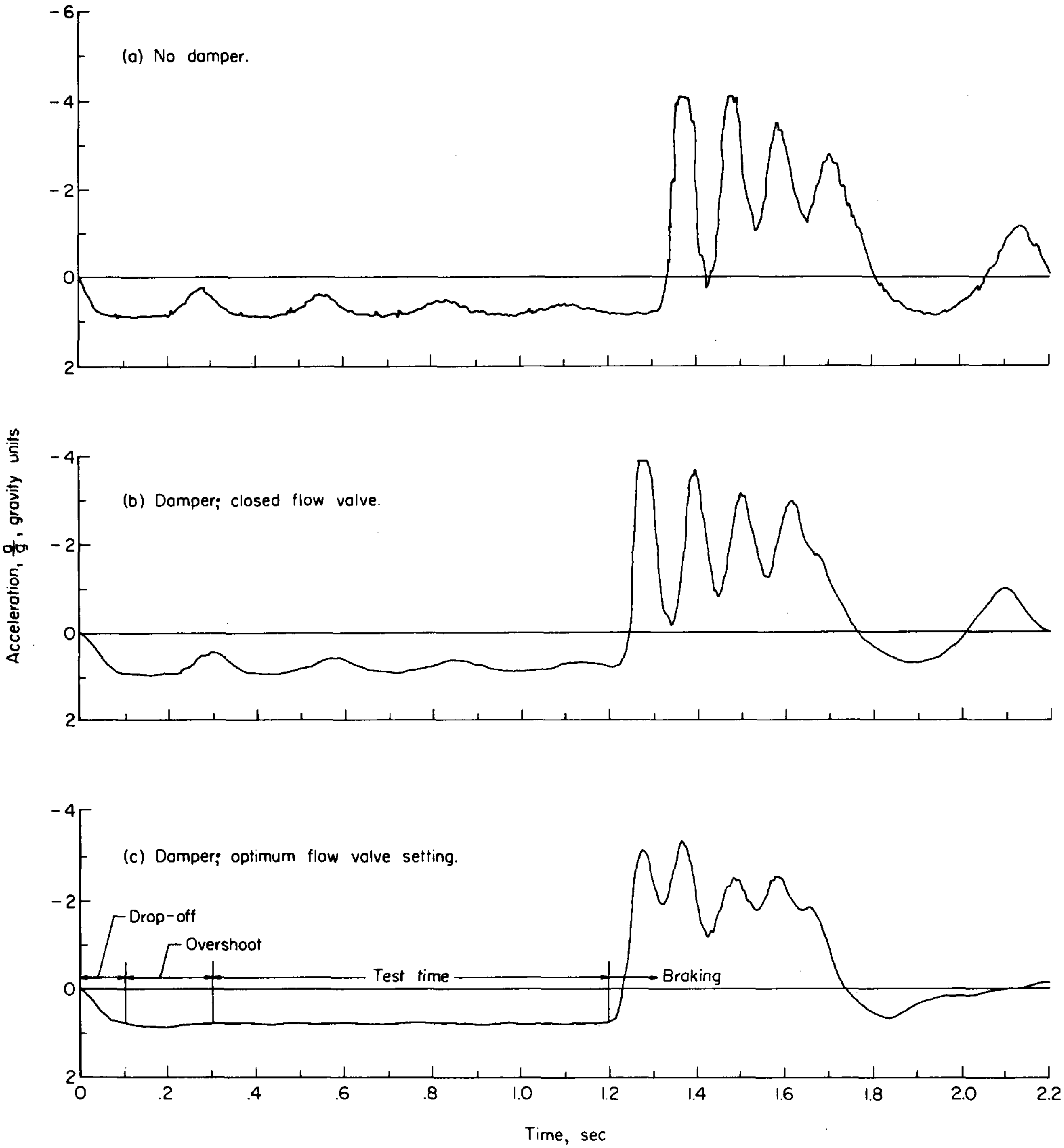


Figure 7.- Typical acceleration-time histories of simulator housing and impact surface before and after addition of damper to eliminate undesirable transient oscillations.

loads on the simulator support structure would be possible since one of the pulleys would be eliminated.

Qualitative Results

In order to assess the differences in the dynamic behavior of simple structures under different gravitational accelerations, tests were conducted

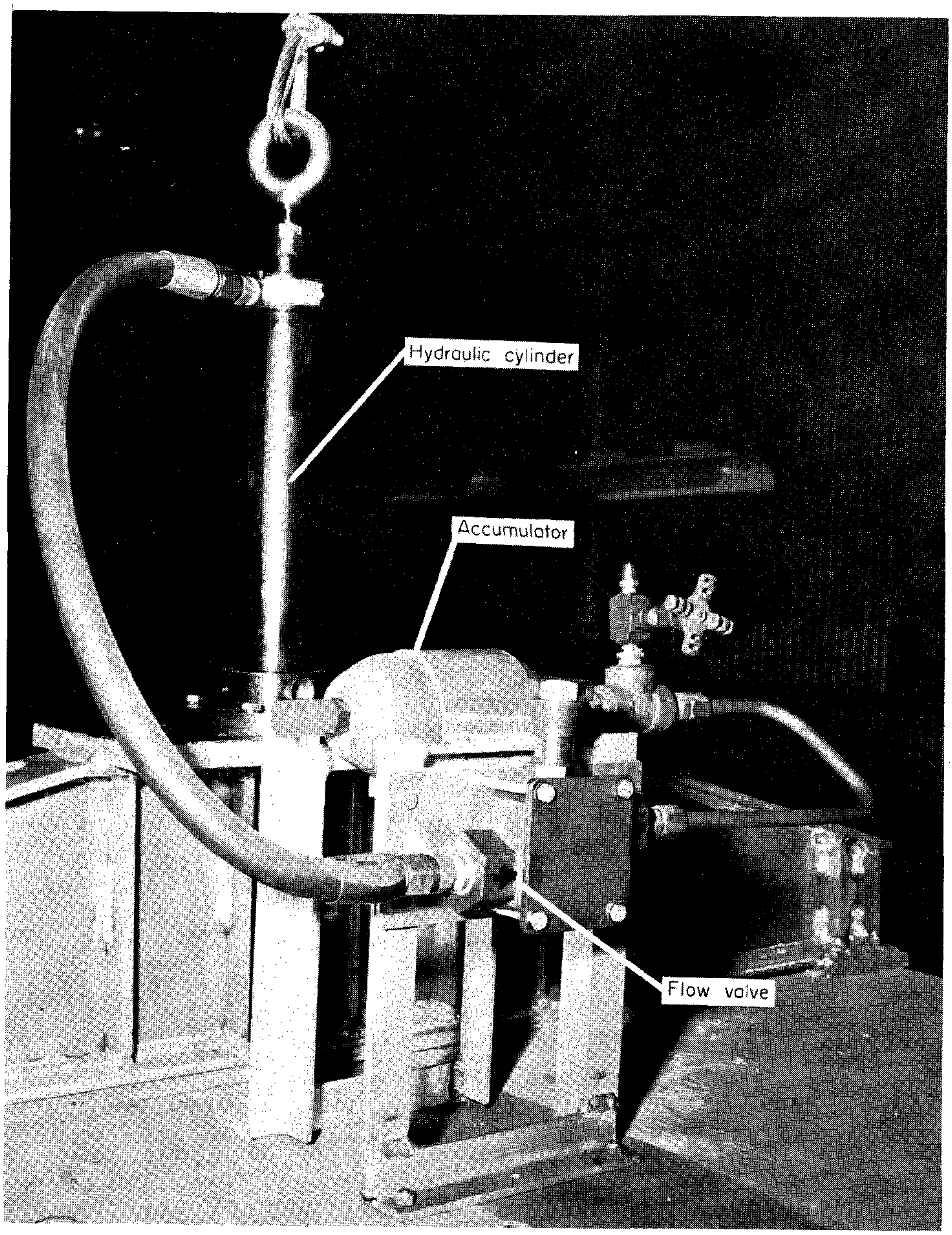


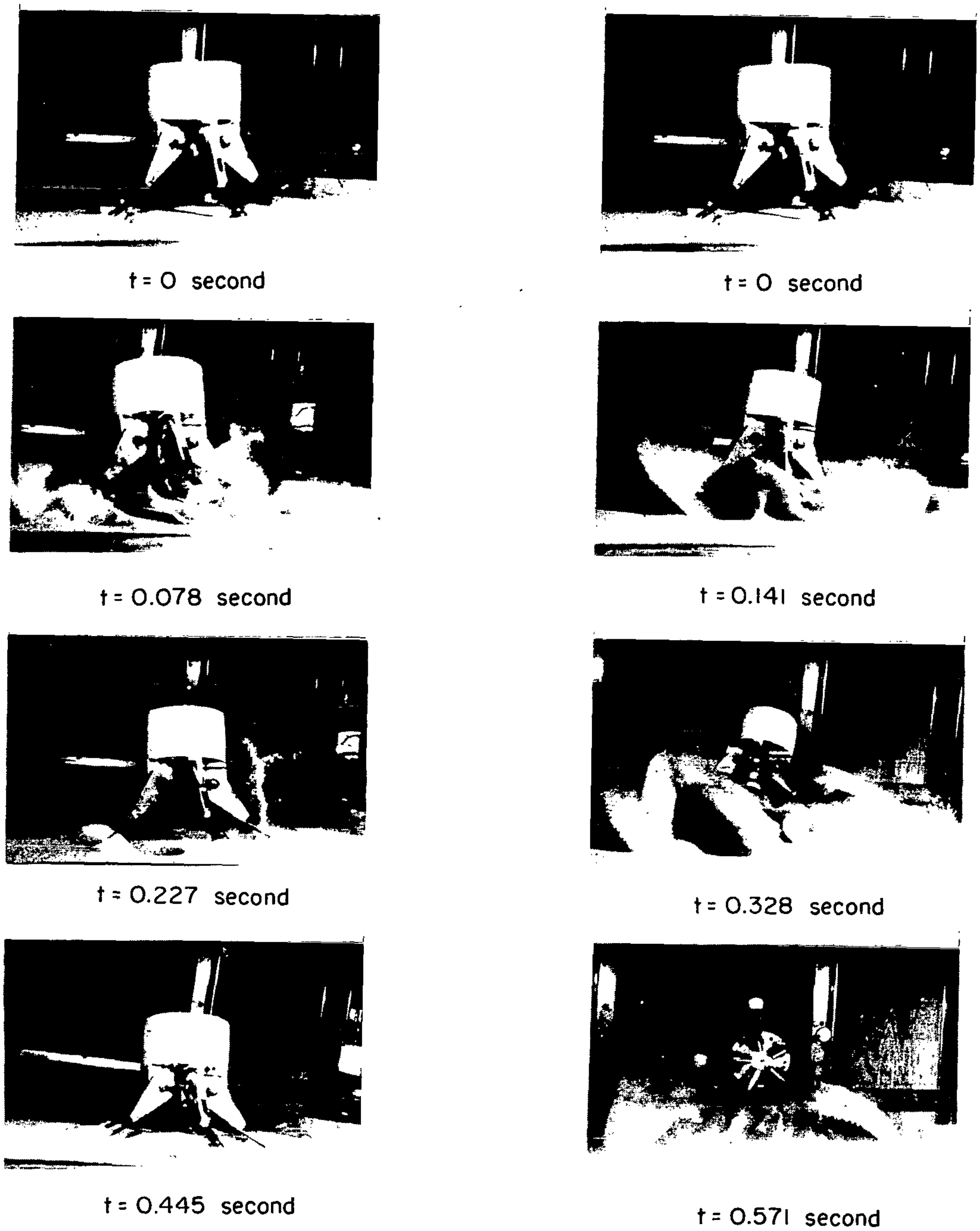
Figure 8.- Hydraulic damper assembly. L-64-529.1

in which the pilot model of the lunar and planetary gravitational simulator was utilized. Through the use of the pilot model simulator, it was possible to determine the landing behavior of simple models impacting under reduced gravitational accelerations and to observe the behavior of surface materials dislodged by the landing gear footpads during initial impact and the subsequent slide-out.

Presented in figures 9 and 10 is a sequence of photographs which illustrates the behavior of the two simple models which were examined in the gravity simulator pilot model. Figure 9(a) shows the behavior of model A impacting under Earth g on a bed of sand, 1-inch deep and with a downhill slope of 5°. The horizontal velocity v_x of the model was 8 ft/sec and the vertical velocity v_y was 11 ft/sec. The photographs show the model at initial impact and during the brief slide-out. As indicated by the photographs, the model exhibited no marked instability. Figure 9(b) presents the model impacting under similar conditions with the exception that the gravitational acceleration was reduced to $\frac{1}{6}$ g. Again the sequence shows the initial touchdown of the model, the slide-out and forward pitching motion. Considerably greater spraying of sand about the model may be noted and the complete pitch-over of the model is vividly demonstrated.

A sequence of photographs is shown in figure 10 which illustrates the behavior of model B impacting on a hard surface and striking two of its legs on an obstacle shortly after landing. As was the case for the tests of model A, the landing surface slope was 5° downhill, v_x was 8 ft/sec, and v_y was 11 ft/sec. The photographs in figure 10(a) show the model landing in a 1 g gravitational field. The model is shown to strike the obstacle and rotate about the front legs and then fall back to the impact surface in a stable condition. The behavior of model B for the same test velocities in a $\frac{1}{6}$ g field is illustrated in figure 10(b) which shows the violent turnover which occurred shortly after the model made contact with the obstacle.

The models used in these tests were not scale models of any particular spacecraft; nevertheless, they serve well to indicate the markedly reduced impact stability which must be expected during landing in reduced gravity fields such as on the Moon or some planets. Although not of primary concern in this particular test program, the behavior of the sand particles dislodged along the landing path by the landing strut footpads is also of interest. It was noted from the tests under a 1 g gravitational field that the sand spray was slight and of little consequence; however, for the same impact velocities of the model under a $\frac{1}{6}$ g gravitational field the trajectory of the dislodged sand particles was considerably higher. This phenomena would, of course, be expected. However, the interesting point was that, even with the small models and the relatively low impact velocities, the maximum height which the sand spray achieved was on the order of the model height. These results are only qualitative in nature but they do suggest that difficulties during landing may be encountered from dislodged surface materials under reduced gravitational accelerations.



(a) 1 g gravitational field. (b) $\frac{1}{6}$ g gravitational field.

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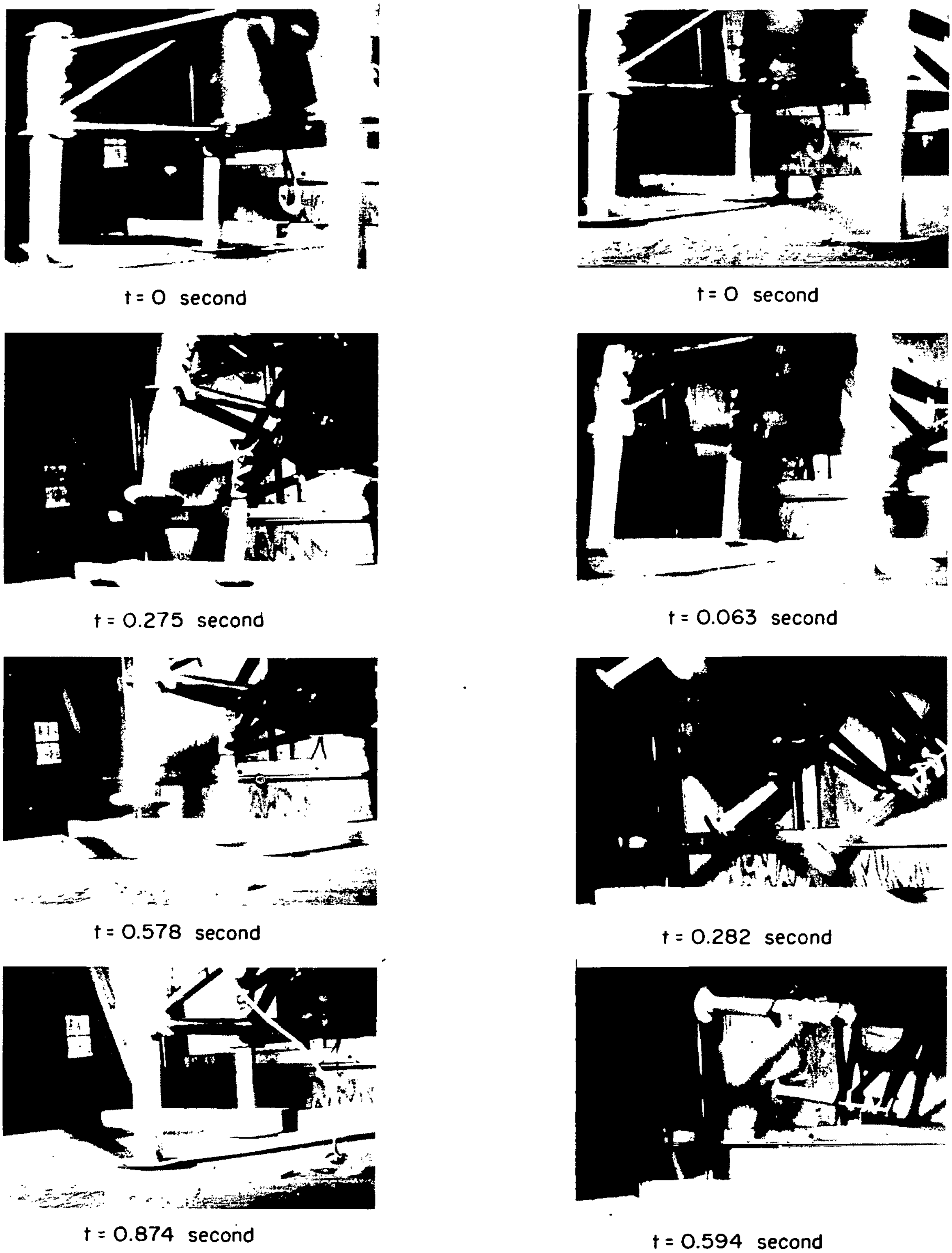
Figure 9.- Photographs of Model A showing impact behavior in two gravitational fields. Sand surface; v_x = 8 ft/sec; v_y = 11 ft/sec; slope, -5°.



(a) 1 g gravitational field.

(b) $\frac{1}{6}$ g gravitational field.

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Figure 10.- Photographs of Model B showing impact behavior in two gravitational fields. Hard surface with obstacle; v_x = 8 ft/sec; v_y = 11 ft/sec; slope, -5°.

Application of Simulator Concept to Large-Scale Structures

In the study of the performance of the pilot model simulator it was found that a 1-second test period was ample to determine the stability of the small models. If, however, the simulator technique were to be considered in a larger facility for reduced-gravity-stability testing of full-scale vehicles (e.g., the lunar excursion module), a considerably longer test time would be required. Calculations indicate that in lunar gravity 4 to 6 seconds would be desirable to determine the stability of a vehicle of this size. The total required drop height in feet, including a 2g braking distance, is approximately twenty times the square of the test time, therefore, for a 4-second test period, 320 feet of drop height would be required. To increase the test time to 6 seconds would require a total distance of 720 feet.

Useful applications of the gravity-simulator technique are not limited, however, to such extreme drop heights. Considerable simplification in design may be realized by limiting the available test time to 1 or 2 seconds. Test times of this order are ample to encompass the initial impact and energy absorption phases of the landing. It would therefore be possible to proof test the structural integrity of the alighting gear under realistic load and gravity conditions by using total drop heights of less than 100 feet. With appropriate instrumentation on the test vehicle, remaining energies and resulting vehicle attitude after impact would be available for use in analytical determinations of the subsequent vehicle motions which would occur in the gravity environment of interest.

It is also of interest to note that a simulator which provides sufficient test times to determine the stability boundaries of a lunar lander would provide even more adequate test durations for determining the stability boundaries in the simulated gravity fields of the planets. The reasons for this are twofold: (1) For a given drop height, the available test time increases as the simulated gravity approaches earth gravity and becomes infinite at 1 g. (2) As the simulated gravitational acceleration increases, increased impact velocities and correspondingly shorter times are required to rotate the vehicle to a marginally stable attitude.

With a full-scale simulator, programed adjustments to the mass of the counterweight or inertia wheel would be required to compensate for aerodynamic drag, pulley friction, and shifting weight of the support cables during the test period. One possible method of compensating for these undesirable forces would be to have the counterweight consist of a tank of water or some other convenient liquid (fig. 1). In this case the mass could easily be adjusted as a function of time by programing the rate of discharge of the fluid during the test.

At the end of the test period, the complete system, including the counterweight or inertia wheel, must be brought to rest by appropriate and positive arresting arrangements. This braking requirement could be met by either a system of brakes on the cables; by a nonlinear arrangement of arresting weights such as anchor chain, or by the use of arresting cables as a brake on the simulator. Because of the required braking distance, the arresting equipment for certain of the braking techniques would have to be located a considerable distance above the ground.

From dynamic considerations, a limit of the payload mass to less than 10 percent of the mass of the impact apparatus is necessary to insure negligible effects of the structure on the behavior of the test vehicle. In addition, due consideration must be given to severe loads on the vehicle structure which may occur during the braking period.

CONCLUDING REMARKS

A technique for the simulation of impact phenomena in lunar or planetary gravitational fields is presented. Tests were conducted in a pilot model simulator which utilized this technique to determine the behavior of simple models under reduced gravitational accelerations. The results and conclusions are summarized in the following paragraphs:

1. The feasibility of the technique for simulation of landing phenomena in lunar or planetary gravitational fields was investigated and demonstrated by a study of the performance of a pilot model simulator which utilized the concept.

2. Results of tests conducted in the pilot model simulator with simple models indicated: (a) the markedly reduced landing stability which must be expected under lunar or other reduced gravitational accelerations and (b) the importance and desirability, if not necessity, of preflight testing of full-scale landing vehicles under realistic gravity conditions.

3. The experimental tests also suggested that difficulties may be encountered from surface materials dislodged during landing under reduced gravitational acceleration because of their considerably higher trajectory about the spacecraft.

4. Several requirements and possible approaches for adapting the technique to large-scale simulator structures are suggested.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 21, 1964.

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The film (16 mm, 6 min, black and white, silent) shows the typical operation of the pilot model of the lunar and planetary gravitational simulator. Typical behavior of two small models landing under Earth's gravitational field and a simulated lunar gravitational field are also shown.

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